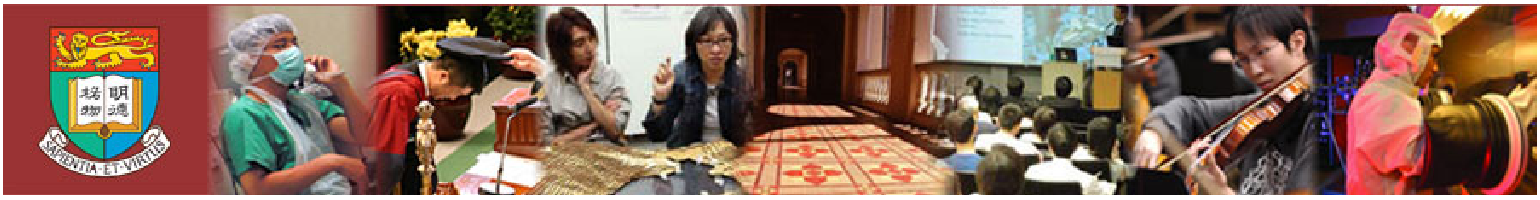

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Author(s)	Ho, Lok-yee; 何樂怡
Citation	Ho, L. [何樂怡]. (2014). Relationship between tone perception and cognitive functions of attention and working memory among normal native speakers of Cantonese. (Thesis). University of Hong Kong, Pokfulam, Hong Kong SAR.
Issued Date	2014
URL	http://hdl.handle.net/10722/238915
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Relationship between tone perception and cognitive functions of attention and working memory among normal native speakers of Cantonese

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A dissertation submitted in partial fulfilment of the requirements for the Bachelor of Science (Speech and Hearing Sciences), The University of Hong Kong, June 30, 2014.

Abstract

This study investigated the relationship between tone perception and cognitive capabilities of attention and working memory in the auditory and visual domains among normal speakers of Cantonese. Fifteen near-mergers (i.e. poor perception of T4/T6 but good production of all lexical tones in Cantonese), and 20 controls (i.e. good perception and production of tones) participated in this study. The Test of Everyday Attention (TEA), the Attention Network Test (ANT), the test of attentional shifting, the digit span backward test and WAIS-IV visual working memory subtests were implemented. Results showed that Near-mergers performed significantly poorer than Controls in divided attention of both auditory and visual domains. Furthermore, the discrimination latency was found to relate to auditory attention and visual working memory. This suggested a modality independent relationship between tone perception and cognitive abilities. It is hypothesized that attention and working memory play a role in modulating the processing speed of tone perception.

Introduction

Previous studies suggest that individual differences in auditory/speech processing are associated with cognitive capabilities such as attention and working memory (Bidelman, Hutka, & Moreno, 2013; George & Coch, 2011; Ho, Cheung, & Chan, 2003; Jess & Janse, 2012; Kraus, Strait, & Parbery-Clark, 2012; Ohala, 1981; Strait, Kraus, Parbery-Clark, & Ashley, 2010; Yu, 2010). For example, Strait et al. (2010) reported that musicians' better performance in attention and working memory tasks, compared with non-musicians, may contribute to their perceptual enhancement in discriminating pitch discrepancies. While many have found a relationship between auditory processing and cognitive abilities, they vary in terms of whether the relationship is modality specific (Ho et al., 2003; Kraus et al., 2012; Strait et al., 2010) or modality independent (Bidelman et al., 2013; George & Coch, 2011; Jess & Janse, 2012). Moreover, many of these studies focused on non-linguistic stimuli and individuals with different experience in musical training. Therefore, the relationship between auditory/speech processing and cognitive functions has been vague with musical training as a confounding factor. The present study sets out to explore the domains and components of cognitive functions related to speech processing.

A few studies have investigated the relationship between cognitive capabilities and speech processing (Jess & Janse, 2012; Kraus et al., 2012; Ohala, 1981; Yu, 2010). Ohala (1981) suggested that speech perception and listeners' ability to correct phonetic variability of speakers' speech are related to a cognitive process. In recognition of speech, listeners might use a top-down analysis which is related to cognitive skills to compensate bottom-up analysis of auditory signals. This suggested that variability in speech perception is attributed to individual cognitive processing styles, which is also supported by Yu's (2010) findings. In that study, English-speaking participants were asked to identify initial consonants /s/ and /ʃ/ under contextual-induced variation. Those who rated themselves as having low communication skills and low attention switching abilities on the Autism Spectrum Quotient (AQ) questionnaire were better at compensating for context-induced variations. Yu (2010) suggested that these people tended to maintain the phonetic distinctions in perception and production of consonants. In light of the relationship between cognitive functions and processing of segmental phonemes, the current study aims to explore how speech processing, particularly processing of suprasegmentals (i.e. lexical tones) in Cantonese, may be related to individual differences in cognitive abilities, namely attention and working memory.

Chinese is a tonal language. Hong Kong Cantonese is well known for its rich system of tonal contrasts. Lexical tone (T), which is a suprasegmental feature carried by each syllable. There are six contrastive lexical tones for open syllables in Hong Kong Cantonese, which are T1 (high-level tone), T2 (high-rising tone), T3 (mid-level tone), T4 (low-falling/ extra low-level tone), T5 (low-rising tone) and T6 (low-level tone). They distinguish between meanings of syllables with an identical segmental structure, for example, /ji1/醫(to cure), /ji2/

椅(chair), /ji3/意(idea), /ji4/疑(suspicious), /ji5/耳(ear) and /ji6/二(two) (Bauer & Benedict, 1997). The pitch contours of the six tones are shown in Figure 1. The six contrastive tones are crowded in a narrow pitch range, hence, tone pairs with similar contours or/and little contrast in pitch height are susceptible to be confused, such as T2 vs. T5, T3 vs. T6 and T4 vs. T6 (Fok, 1974; Fung & Wong, 2010a, 2010b).

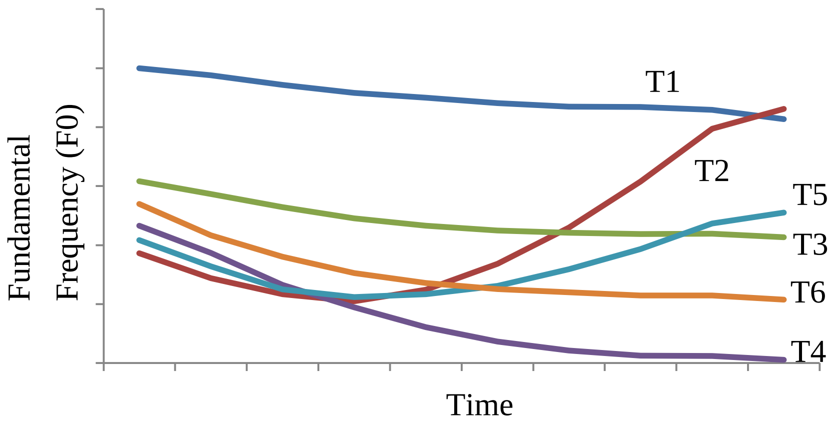

Figure 1. The pitch contours of the six contrastive tones in Hong Kong Cantonese

In recent years, the merging of Cantonese tones has been a subject of investigation (Fok, 1974; Fung & Wong, 2010a, 2010b; Law, Fung, & Kung, 2013; Mok & Wong, 2010a, 2010b; So, 1996). Some normal speakers fail to distinguish some of the six contrastive tones in perception and/or production of speech. In Fung and Wong (2010a, 2010b), 120 native Cantonese normal speakers in Hong Kong were assessed on their perception and production of the six contrastive lexical tones in Cantonese. Particular tone pairs were in different stages of merging, with participants showing different patterns of tone perception and production. One of the examples was T2/T5 contrast, in which a significant number of participants in Fung and Wong (2010a, 2010b) failed to distinct the two tones in perception and production.

This group of participants was called full mergers. Another example was the T4/T6 contrast, in which some participants were able to distinctively produce the two tones but failed to discriminate them in perception. This group of participants was called near-mergers. These results revealed that many normal speakers may not be able to discriminate or/and produce all six tones. Normal speakers cannot be expected to be one hundred percent correct in tone discrimination and production, as most researchers and clinicians (e.g. speech therapists) do. Therefore, this situation has provided a very interesting context for studying individual differences of speech processing between normal speakers who demonstrate merging of tones and normal speakers who do not merge tones in perception or production.

The near-merger phenomenon, as also found in T4/T6 of Hong Kong Cantonese (Fung & Wong, 2010a), has been perplexing and controversial among phonologists/phoneticians. The dissociation between poor discrimination and good production of tones challenges dominant models of phonological processes which emphasize that production of speech requires access to sensory or phonological representations which are related to speech perception (Galantucci, Fowler, & Turvey, 2006; Hickok & Poeppel, 2007). According to those models, only good perception and poor production is possible but not vice versa. In addition, previous studies such as Fung and Wong (2010a, 2010b) used behavioral tasks for discriminating or identifying tones, which may involve judgments and decisions, and thus may not truly reflect the processing of auditory information. These have motivated Law et al. (2013) to investigate the near-merger phenomenon by observing neural responses in brain level by neuroimaging methods and to observe any cognitive differences between participants with and without dissociation. In that study, there were two groups of native normal speakers of Cantonese: the control group (speakers who could discriminate and produce all six contrastive tones) and the near-merger group (speakers who could distinctively produce T4/T6 but failed to discriminate them in perception). A lexical syllable /fu/ and a non-lexical syllable /lu/ carrying T1, T4 and T6 were included as stimuli. An event-related potential (ERP) study with a passive oddball paradigm was implemented. Participants were instructed to pay attention to a silent movie while ignoring the sounds they were hearing. Group differences were observed in terms of the mismatch negativity (MMN) and P3a with respect to pairs of lexical or non-lexical syllables with small (T4/T6) or big (T1/T6) tone contrasts. Both MMN and P3a are ERP components that can be obtained in the absence of the participants’ attention (Näätänen, Paavilainen, Rinne, & Alho, 2007). MMN can be elicited in response to a change in the physical properties of a repeated sound, for example, pitch and frequency. It is an index of auditory working memory as it depends on the existence of a short-term memory trace of the preceding auditory stimuli in the auditory cortex to detect a change in upcoming auditory signals (Näätänen, et al., 2007). P3a is associated with participant’s switching of attention in the presence of a deviance in unattended sound sequence and thus is an index of involuntary attention switching (Näätänen et al., 2007). In Law et al. (2013), the existence of near-merger phenomenon was confirmed by the presence of MMN to T1/T6 and null response to T4/T6 of lexical syllables in the near-merger group. The results also showed a tendency that the P3a response of the control group was stronger than that of the near-merger group, hence, the authors hypothesized that the control group might have higher cognitive capability in terms of automatic attention switching, as indicated by P3a, and perhaps other components in attention networks and working memory. Another recent study by Mok, Zuo, and Wong (2013) reported that compared with participants with good production and perception of tones, tone-mergers had comparable accuracy but longer reaction time in a tone discrimination task for both AA (same stimuli) and AB (different stimuli) trials. Mok et al. (2013) hypothesized that the slower response in tonal discrimination of the merging participants indicated their needs of longer processing time for making the correct decisions. This might raise the possibility of the role of cognitive functions in tone perception as well.

The current study assesses the hypothesis of a relationship between cognitive abilities and tone perception/production, as raised by Law et al. (2013) and Mok et al. (2013). This study aims to 1) compare and identify any difference in cognitive performances of the T4/T6 near-merger participants and that of the control participants, and 2) identify the components of attention and working memory in the visual and auditory domains that are related to the differences in tone perception.

Methods

Ethics statement

Informed written consent forms in both Chinese and English version were signed by each participant before the experiment began. The experiment was performed with the approval of the University of Hong Kong Human Resource Ethics Committee for Non-Clinical Faculties. Participants were paid.

Participants

Fifty native speakers of Cantonese were recruited in this study. The participants included adults who (i) spoke Cantonese as their first language, (ii) were born and raised in Hong Kong, (iii) attended mainstream schools in Hong Kong, and (iv) showed no evidence or history of neurological dysfunctions, socio-emotional problems, hearing impairment or speech and language impairment. All participants completed a screening test which was composed of tone perception and speech production. On the basis of their performance in the screening test, 35 participants were invited to carry out a battery of cognitive tests and they were classified into two groups: the Control group (N = 20, female = 6) and the Near-merger group (N = 15, female = 8); while the remaining 15 participants did not fulfill the inclusion criteria for both groups. The characteristics of the participant groups were shown in Table 1. Control had age ranged from 18 to 26 years while Near-merger had age ranged from 18 to 39 years. In view of previous studies reporting that musical experience may be a factor of cognitive capabilities

(Bidelman et al., 2013; George & Coch, 2011; Kraus et al., 2012), it was ensured that the two participant groups had comparable musical background in terms of onset [$t(33) = .13$, $p = .896$] and duration [$t(33) = .60$, $p = .550$] of training.

Table 1. Means and standard deviations (SD) of characteristics of the two participant groups.

Group		Age	Musical training		Accuracy (%)	
			Onset (years)	Duration (years)	Overall tone perception	Overall tone production
Near-merger	Mean	23.80	5.53	2.60	83.96	95.88
	(SD)	(5.54)	(7.31)	(3.66)	(5.80)	(4.06)
Control	Mean	22.60	5.85	3.45	98.62	99.10
	(SD)	(2.41)	(6.78)	(4.43)	(1.84)	(2.36)

Screening

Stimuli

The lexical syllable /fu/ was selected as stimuli. It was chosen since the combinations of the syllable /fu/ with each of the six contrastive lexical tones form existing syllables and can be presented in written characters: /fu1/ (husband, 夫), /fu2/ (bitter, 苦), /fu3/ (trousers, 褲), /fu4/ (symbol, 符), /fu5/ (woman, 婦) and /fu6/ (negative, 負). The six syllables were produced and recorded by a native female Cantonese speaker, which served as the auditory stimuli of the tone discrimination task. The length of the stimuli was 500 ms and the intensity was 70 dB SPL. These six Chinese characters were used in reading aloud task as well.

Procedures

A reading aloud task and a tone discrimination task were administered in a sound attenuated booth in the Laboratory for Communication Science in the Division of Speech and

Hearing Sciences at the University of Hong Kong. The tasks were conducted to the participants using the Presentation software running on an IBM laptop. Instructions of the tasks were written in Chinese presented on the computer screen and were read aloud in Cantonese simultaneously (See Appendix A). Practice with ten trials was given before the beginning of each task. The reading aloud task was conducted before the perception task to eliminate priming effect. The screening lasted approximately for an hour.

Tone discrimination task

An AX (same-different) discrimination task was administered. The six contrastive tones of /fu/ formed 36 tonal pairs (6 AA pairs vs. 30 AB pairs counterbalanced in order of syllables). Each tonal pair was repeated ten times. A total of 360 trials were presented binaurally to each participant through a headphone and the trials were randomized for each participant. Participants were required to indicate on each trial whether the two aurally presented tones were identical or different by clicking the left or right button of a mouse as quickly and accurately as possible. The accuracy and latency of response of each trial were recorded. The reaction time (RT) was calculated from the onset of the second syllable.

Reading aloud task

Each of the six written Chinese characters was embedded into two carrier phrases in the middle and final positions of the sentence: / ŋɔ5 ji4 ka1 tok6 ___ tsi6/ (I am now reading the ___ character, 我而家讀 ___ 字) and / ni1 kɔ3 tsi6 hɐi6 ___ / (The character is ___ , 依個

字係 ___). Each sentence was repeated ten times, giving a total of 120 trials (6 tones x 2 types x 10 repetitions). The written sentences were presented to each participant randomly and their speech outputs were recorded digitally for phonetic transcription by two native Cantonese raters who were able to distinguish all six tones in perception and production and were blinded to the stimuli. The accuracy of production of each tone was analyzed.

Selection and Grouping of participants

Participants of the control group met the following criteria: 1) accuracy of perception task of all tonal pairs was above 90%, and 2) accuracy of production task was above 90%. Participants of the near-merger group met the following criteria: 1) accuracy of discriminating tonal pairs of T4/T6, T4/T4, T6/T4 and T6/T6 was below 85%, and 2) accuracy of production task was above 85%. Different cutoffs for the production scores of the two groups were used due to the difficulty in recruiting participants. For the control group, there was no significant difference between the accuracy of perception of all tonal pairs and that of production of all tones [$t(19) = -.72$, $p = .481$]. For the near-merger group, the accuracy of overall tone perception was significantly lower than that of the overall tone production [$t(14) = -6.92$, $p < .001$]; accuracy of perception of T4/T6 tonal pair was significantly lower than that of production of T4 and T6 [$t(14) = -8.41$, $p < .001$]; accuracy of perception task of T4/T6 tonal pair was significantly lower than that of the remaining tonal pairs [$t(14) = -10.26$, $p < .001$]; and accuracy of production of T4 and T6 was not significantly different from that of other tones [$t(14) = -.05$, $p = .962$]. When comparing the two participant groups, Near-mergers had significantly poorer performance on perceiving T4/T6 pairs than Controls [$t(33) = 10.62$, $p < .001$], but comparable performance on other tone pairs [$t(33) = .29$, $p = .776$] (See Table 2).

Table 2. Accuracy and reaction times of tone discrimination between the two groups.

Tone pairs	Group	Mean accuracy (%) (SD)	Mean reaction time (ms) (SD)
T4/T6	Near-merger	69.33 (11.24)	1218.45 (222.78)
	Control	97.75 (3.23)	1095.75 (120.22)
Others	Near-merger	98.59 (1.36)	1114.80 (185.64)
	Control	98.76 (1.94)	992.54 (89.56)

Based on ten percent of the transcription of production task, an inter-rater reliability analysis using the Kappa statistic was conducted to observe the consistency between the two raters. The agreement between the two raters' judgment was high, $\kappa = .95$ ($p < .001$).

Attention and working memory tasks

Attention in the auditory domain was assessed by the auditory subtests of the Test of Everyday Attention (TEA) (Robertson, Ward, Ridgeway, & Nimmo-Smith, 1994) and the test of attentional shifting (Helenius, Uutela, & Hari, 1999; Lallier et al., 2009); while visual attention was examined by the visual subtests of TEA and the Attention Network Test (ANT) (Fan, McCandliss, Sommer, Raz, & Posner, 2002). Auditory working memory was assessed by the backward digit span test (Lee, Yuen, & Chan, 2002) while visual working memory was assessed by WAIS-IV visual working memory subtests (Wechsler, 2008).

Procedure

The 35 participants selected were re-invited to complete the five cognitive tests in the aforementioned sound attenuation booth. All tests were administered according to the standard instruction, which was translated into Cantonese (See Appendix A). The five tasks were rotated across participants. Three minutes break was given in between tasks. The experiment lasted about one and a half hour.

The Test of Everyday Attention (TEA)

The Test of Everyday Attention (TEA) (Robertson et al., 1994) is a comprehensive test battery of attention which covers different aspects of attention, i.e. selective, sustained, divided attention and attentional switching in the auditory and/or visual domain(s). It is based on an imaginary scenario of a vacation trip to the Philadelphia area of the United States and is culturally appropriate for healthy Hong Kong Chinese (Chan, Lee, & Hoosain, 1999).

According to Cohen (1993), selective attention refers to the ability to give attentional priority to some informational elements over others; sustained attention refers to the ability to maintain attention over a relatively long time on a task; divided attention refers to the ability to divide attention among a multitude of processes and potential stimuli; attentional switching refers to the tendency to orient and shift attention to new events while inhibiting the old ones.

Each participant was given six subtests of the TEA. Scaled scores of each subtest were obtained based on their individual raw score from the test manual. The six subtests include “map search” and “telephone search” that assess visual selective attention; “elevator counting with distraction” that examines auditory sustained attention; “telephone search dual task” which assesses divided attention in the auditory and visual domains; “visual elevator” which assesses visual attentional switching; and “elevator counting with reversal” which assesses auditory attentional switching (See Appendix B for description). The TEA lasted 30 minutes.

The Attention Network Test (ANT)

The Attention Network Test (ANT) was developed based on Posner and Peterson’s (1990) neuroanatomical model of attention, in which the attention system is divided into three attentional networks, including alerting, orienting and executive control. Alerting system involves in achieving and maintaining a state of alertness to process incoming high priority signals. Orienting system refers to the selection of particular information from several sensory inputs. Detecting and resolving conflicts among responses involves the executive control.

The ANT is a combination of the cued reaction time and the flanker task (Fan et al., 2002). Efficiency of the three attentional networks in the visual domain is assessed by measuring how reaction times are influenced by alerting cues, spatial cues and flankers (See Appendix B for the scoring system). The stimuli were presented visually via E-prime running on a desktop. There were 144 trials, including 24 stimuli repeating six times. The 24 stimuli were formed from two targeted arrow locations (above and below a centrally located fixation cross), two targeted arrow directions (left and right), two flanker conditions (congruent and incongruent) and three warning conditions (no-cue, alerting-cue and spatial-cue). The trials were randomized for each participant. Participants were instructed to focus on the fixation cross throughout the task, and identify whether a central arrow points to the left or right by pressing a button of a mouse as quickly and accurately as possible. The ANT took 20 minutes to complete.

The test of attentional shifting

Auditory stream segregation task was administered to assess the ability of attentional shifting in the auditory modality that was estimated by the threshold of the stream segregation (Helenius et al., 1999; Lallier et al., 2009). The stimuli were presented via E-prime running on a desktop and presented binaurally through a headphone. There were 30 tone sequences composed of alternating 1000- and 400-Hz pure tones, with each sequence lasting five seconds. At the end of each tone sequence, participants had to indicate whether they perceived “one stream” or “two streams” by pressing the corresponding keyboard button according to a forced choice paradigm. A simple "one-up, one-down" adaptive method was implemented to estimate the 50% chance level in the two forced choice paradigm. The program automatically decreased or increased the stimulus onset asynchrony (SOA) after the response was “one stream” or “two streams” respectively. The auditory stream segregation threshold was obtained by taking the mean of the SOAs of the last ten trials. This test lasted 15 minutes.

The backward digit span test

The backward digit span test measures one’s capability of central executives under auditory working memory, which has a significant role in controlling the other three subsystems of working memory, i.e. phonological loop, visuo-spatial sketchpad and episodic buffer (Baddeley, 2003; Lee et al., 2002). The central executives manipulate temporary stored information and regulate cognitive processes involving allocation of the limited attentional capacity. In this test, participants listened to a sequence of digits spoken by a native Cantonese female speaker and repeated the digits in the reverse order. The task began with a span of two digits. There were two trials per span level. When a participant was able to answer at least one trial correctly, s/he would go to the next level and one digit would be added at each level. An individual's digit span was determined when two consecutive mistakes in the same span level were committed (Lee et al., 2002). The score was the maximum number of digits correctly repeated in the reverse order. This test lasted ten minutes.

WAIS-IV visual working memory subtests

WAIS-IV visual working memory subtests were part of a standardized intelligence test (Wechsler, 2008). It assesses the cognitive processing speed of individuals in the visual domain. Each participant was given three tasks, including symbol search, coding and cancellation (See Appendix B for description). They were required to visually search, and cross or draw symbols within time limit. Scaled scores of each task were obtained by converting their individual raw score according to the test manual. This test lasted 15 minutes.

Data and statistical analysis

Multiple independent t-tests were used to evaluate the statistical significance of differences between the participant groups in terms of their performance in the five tests of attention and working memory. There were 16 dependent variables (DVs) as shown in Table 3, and two levels of one independent variable, i.e. the control group and the near-merger group. Significance threshold was adjusted for multiple comparisons of DVs (p = .05/16 = .003).

Table 3. The 16 dependent variables for multiple independent t-tests.

Cognitive tests	Dependent variables
The Test of Everyday Attention (TEA)	Eight scaled scores of the six subtests
The Attention Network Test (ANT)	Calculated response times of the three attentional networks
The test of attentional shifting	Threshold of auditory stream segregation
Backward digit span	Span size
WAIS- visual working memory subtests	Scaled scores of the three tasks

In addition, an independent t-test was conducted to examine any significant difference in reaction times in the tone discrimination task among the participant groups as suggested by Mok et al. (2013). The average value of individual's reaction times of all tone pairs except T4/T4, T4/T6, T6/T4 and T6/T6 was considered. Near-mergers were expected to have low accuracy at discriminating T4/T6 pairs and they may complete those trials by guess. The reaction times of T4/T6 obtained from Near-mergers were not valid observations and thus they were excluded in calculation.

To explore any relationship between discrimination latency and components of cognitive functions, multiple regression analysis was conducted. Auditory and visual attention, and auditory and visual working memory were the four areas of interest. Auditory working memory was indicated by the span size of the backward digit span test. The remaining three cognitive areas were indicated by three composite scores. The TEA auditory composite score was formed from summing the standard-scores (Z-scores) of auditory subtests of TEA (i.e. “Elevator counting with distraction”, “Elevator with reversal” and “Telephone search dual task”). It indicated auditory attention. Visual attention was measured by the TEA visual composite score from visual subtests of TEA (i.e. “Map search”, “Visual Elevator” and “Telephone search”). The Visual working memory composite score was generated by summing the Z-scores of the three subtests of WAIS-visual working memory subtests (i.e. “Symbol search”, “Coding” and “Cancellation”). It reflected visual working memory. The correlation among the three composite scores, the scores from the ANT, the test of attentional shifting and the backward digit span test, and the reaction times in discrimination of all tonal pairs except T4/T6 was examined. Those scores that showed significant correlation ($p < .05$) with reaction times were entered as predictor variables and discrimination latency of all tonal pairs except T4/T6 as outcome variable in the subsequent stepwise regression analysis.

Results

Cognitive measures

The means and standard deviations of 16 dependent variables of the cognitive measures between the two groups were shown in Table 4. The multiple independent t-tests revealed a significant effect of group on one cognitive measure - the Telephone Search Dual task of TEA [$t(33) = 3.17$, $p = .003$], which assesses divided attention in the auditory and visual domains. Near-mergers had a lower score in the Telephone Search Dual task than Controls. None of the other measures showed significant differences between the two groups (all $p > .003$).

Table 4. Means and standard deviations (SD) of cognitive measures among the groups.

Task	Control		Near-merger		*p* value
	Mean	(SD)	Mean	(SD)	
TEA - Map search in first minute	11.45	(2.16)	11.07	(2.69)	.643
TEA - Map search in two minutes	9.05	(2.14)	9.13	(3.64)	.933
TEA - Telephone search	15.85	(3.50)	13.20	(2.86)	.023
TEA - Elevator counting with distraction	12.40	(1.50)	11.47	(2.80)	.213
TEA - Telephone search dual task	13.25	(3.29)	10.20	(2.01)	.003
TEA - Visual elevator (accuracy)	11.10	(2.67)	12.47	(1.77)	.096
TEA - Visual elevator (reaction time)	14.55	(3.47)	11.93	(2.25)	.016
TEA - Elevator with reversal	11.95	(1.96)	11.40	(2.06)	.427
ANT - Alerting effect	26.19	(13.65)	20.74	(16.25)	.289
ANT - Orienting effect	34.93	(20.31)	33.35	(20.64)	.823
ANT - Executive control	70.56	(18.82)	78.19	(29.61)	.359
Threshold of the stream segregation	61.67	(34.90)	70.76	(49.81)	.529
Backward Digit Span task - Span size	7.95	(1.57)	7.40	(1.81)	.343
WAIS-IV - Symbol search	15.35	(2.82)	14.27	(3.22)	.297
WAIS-IV - Coding	16.65	(2.78)	15.87	(3.23)	.446
WAIS-IV - Cancellation	13.00	(3.20)	11.93	(2.87)	.315

Reaction times of perception of tonal pairs

Excluding tonal pairs T4/T4, T4/T6, T6/T4 and T6/T6, Controls had a range of reaction times (RTs) of 836.813 ms to 1134.571 ms while Near-mergers' reaction times ranged from 828.762 ms to 1423.711 ms (See Table 2). The independent t-test revealed a significant effect of group on RTs [$t(33) = -2.581$, $p = .015$]. Near-mergers had longer RTs in tone discrimination than Controls.

Relationship between reaction time in tone discrimination and cognitive functions

In light of the significantly longer RTs in tone perception observed in Near-merger, correlation analysis was conducted to explore the relationship between RTs in tone perception and cognitive functions among all participants irrespective of their group status. The RTs of all tonal pairs except T4/T4, T4/T6, T6/T4 and T6/T6 trials were significantly correlated with TEA auditory ($p < .01$), TEA visual ($p < .05$), visual working memory (WM) ($p < .01$) and the measure of alerting effect in ANT ($p < .05$) as shown in Table 5. The association between the RT and the four cognitive measures were further explored by multiple regressions. Stepwise regression revealed visual WM and TEA auditory as significant predictors, accounting for 32.6% of the variance [$R^2 = .326$, $F(2, 32) = 9.238$, $p = .001$] (see Table 6).

Table 5. Correlation matrix between RT of tone perception and cognitive measures.

	Overall RT[#]	AE	ASS	BDS	TEA auditory	TEA visual
AE	-.360*					
ASS	-.005	.361*				
BDS	.024	.194	.033			
TEA auditory	-.445**	.120	-.024	.172		
TEA visual	-.401*	.292	-.170	.111	.511**	
Visual WM	-.522**	.505**	.092	.203	.293	.450**

*: $p < .05$, **: $p < .01$, [#] all tone pairs except T4/T4, T4/T6, T6/T4 and T6/T6. AE: Alerting effect in ANT, ASS: Auditory stream segregation, BDS: Backward Digit Span.

Table 6. Stepwise regression for RT of all tone pairs except T4/T6 with four cognitive measures including TEA auditory, TEA visual, visual WM and Alerting effect in ANT

	B	Standard Error *B*	Beta β	*t*	*p*
Step 1					
Constant	1044.934	21.921			
Visual WM	-32.449	9.228	-.522	-3.516	.001
Step 2					
Constant	1044.934	20.782			
Visual WM	-26.624	9.150	-.428	-2.910	.007
TEA auditory	-24.604	11.328	-.320	-2.172	.037

Note. $R^2 = .251$ for Step 1 ($p = .001$); $\Delta R^2 = .326$ for Step 2 ($p = .001$).

Discussion

The purpose of the present study was to explore individual differences in the components of attention and working memory in the auditory and visual domains that are related to tone perception. In this study, we examined the possible differences in cognitive functions between participants with good perception and production and participants with good production but poor perception of tones in Cantonese using a battery of cognitive tests. The results of multiple independent t-tests revealed that compared with Near-mergers, Controls demonstrated an enhanced ability in divided attention in the auditory and visual domains, whereas no statistically significant difference was found in the performance of working memory measures between the two participant groups. Nonetheless, the two groups were found to have statistically significant difference in the speed of tone discrimination. Near-mergers showed longer reaction time in all trial types than Controls. This longer response time was further revealed to be related to attention in the auditory domain and working memory in the visual domain when combining the two groups using multiple regressions analysis.

It was interesting to find that Controls demonstrated higher performance in cognitive functions in the visual domain apart from the auditory domain, relative to Near-mergers. Controls significantly performed better in the dual task which indicated divided attention in the auditory and visual domains. This result was incompatible with some previous studies which suggested that people with higher performance in auditory or speech processing have cognitive function enhancement in the auditory domain but not other domains (Ho et al., 2003; Strait et al., 2010). Our results, however, agreed with those studies which supported a relationship between auditory/speech perception and cognitive functions in both auditory and visual domains (Bidelman et al., 2013; George & Coch, 2011; Jess & Janse, 2012). Therefore, our findings support the notion that tone perception is associated with domain general cognitive abilities.

Apart from having lower accuracy in differentiating T4/T6 pairs, Near-merger was slower than Control in discriminating lexical tones. In Mok et al. (2013), tone mergers who had relatively poor production of tones but comparable accuracy of tone discrimination had longer reaction time in tone discrimination than participants with good production and perception of tones. The longer discrimination latency found in speakers with non-distinctive perception in the current study is compatible with the study of Mok et al. (2013). In addition, the reaction time in tone discrimination was found to be associated with auditory attention and visual working memory. This is consistent with our group comparison findings that tone perception is related to domain-independent cognitive capabilities. It is hypothesized that with higher performance in auditory attention and visual working memory, the participants were able to respond faster in the tone discrimination task. Specifically, better auditory attention to the auditory stimuli such as lexical tones enhances the processing in the auditory cortex. This may lead to faster discrimination of tones in Controls.

The present study was nonetheless, inconsistent with previous studies that found a role of auditory short-term memory and working memory, indicated by the ability to recall words, numbers or pitches, in auditory processing (Bidelman et al., 2013; Kraus et al., 2012). By using the backward digit span task, Kraus et al. (2012) consistently found a role of auditory working memory in auditory processing. Our study also implemented backward digit span task to examine auditory working memory, however no relationship between auditory working memory and tone perception was found. Conway et al. (2005) proposed that the backward digit span task was only a mental transformation task and it was not demanding enough to turn an immediate-memory task into a working memory capacity task. In addition, compared with visual working memory tasks which emerged as a significant predictor of discrimination latency, the backward digit span task does not contain a speeded component. Thus, it may be less sensitive in identifying differences in auditory working memory between the two participant groups. Further research on relationship between auditory working memory and tone perception shall involve a task with speeded component and more demanding, such as operation span task (Conway et al., 2005).

Apart from implementing only the backward digit span task to examine participants' auditory working memory, certain limitations were also noted in the present study. Since it was of great difficulty in identifying Near-mergers who met our inclusion criteria, the sample size in our study was relatively small. More participants should have recruited.

In addition, only T4/T6 near-mergers were investigated in the present study. To further our understanding of the relationship between tone perception/production with cognitive functions, merging of other tone-pairs can be investigated to see if it is consistent with our findings, and whether there are differences in cognitive functions related to tone processing among speakers with merging in perception only (i.e. near-merger), merging in production only (i.e. partial-merger) and merging in both perception and production (i.e. full-merger). Furthermore, only behavioral measures were implemented to examine participants' cognitive functions. Further research using neuroimaging method such as event-related potentials (ERP) to study the neural aspect of attention and working memory in the visual and auditory domains would help to see if the results support the findings from behavioral measurements in the current study. Last but not least, since musicians have enhanced cognitive functions related to auditory/speech perception and tone perception is related to cognitive functions, investigation shall be carried out to evaluate the efficacy of music training in intervening speakers who have poor tonal perception.

Clinical implications on speech and language development of children

Previous studies suggested sensitivity to lexical tones is one of the aspects of phonological awareness that is important in early reading development in Chinese, and tone is important for Chinese character recognition (Chen et al., 2004; Fu & Huang, 2000; Hu &

Catts, 1998). In the study of McBride-Chang et al. (2008), performance in tone perception was found to be one of the indicators for children who are at risk of language delay or reading disability. That means pre-school children with poor tone discrimination and/or identification may be at risk of developing into dyslexia at school-age when they have to learn and use literal language. Similarly, Cheung et al. (2009) provided evidence that Chinese children with dyslexia demonstrated a poorer performance in tone discrimination than those without reading difficulties. Our study suggested a relationship between tone perception and attention and working memory. Further research should investigate whether children with dyslexia or at risk of reading disabilities have poorer cognitive functions than those without reading problems, and whether training on those cognitive functions can help intervening children with dyslexia.

Conclusion

The present study supported a relationship between auditory attention and visual working memory in tone perception among normal speakers of Cantonese. Speakers with good production and perception of tonal contrast were found to have an enhanced ability in divided attention in the auditory and visual domains than speakers with good production but poor perception of lexical tones (near-mergers). Further research should investigate the cognitive functions related to tone perception using non-behavioral measures such as event-related potential paradigm, and observe any differences among different types and stages of tone mergers (i.e. full-mergers, partial-mergers, near-mergers and controls).

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Acknowledgement

I would like to express my sincere gratitude to Dr. Sam-po Law for her guidance, comments and supports on the present study. I wish to thank Ms. Jinghua Ou for her assistance and encouragement throughout the course of the study. I would like to thank all participants for their time and effort in the experiment. I would also like to thank my family and friends for their unconditional supports. Thank you God for everything.

Appendix A.

Part I - Cantonese instructions of reading aloud task and tone discrimination task

Instruction of the reading aloud task

非常感謝及歡迎你參與是次發音實驗。是次實驗一共有四個部份，每個部份有三十組題目。於每組題目中，你會看到一句句子，請你大聲讀出這句句子。現在請先試做一下。

Instructions of the tone discrimination task

是次聽辨實驗總共有十個部份。於每條題目中，你會聽到兩個單音，你需要判斷這兩個音是「一樣」 或是「唔一樣」，並按滑鼠上相應的鍵，左邊鍵：一樣，右邊鍵：唔一樣。請你儘快作答，否則會自動進入下一題，現在請先試做一下。

接下來的題目中，你同樣會聽到兩個單音，你需要判斷這兩個音是「一樣」 或是「唔一樣」，並按滑鼠上相應的鍵，左邊鍵：唔一樣，右邊鍵：一樣。請你儘快作答，否則會自動進入下一題，現在請先試做一下。

Part II - The translated Chinese instructions of the five cognitive tests (Please refer to the manual of the published tests for English instructions.)

Instructions of the Test of Everyday Attention (TEA)

Subtest 1: Map Search

這裡的符號顯示在費城地區哪裡可以找到餐館。在地圖中有很多像這樣的標誌。假如，你現在和一個家庭成員或朋友一起，他們在駕駛，而你正在導航。你想知道餐館位於哪些地方，來決定你們在哪裡吃飯。請你在兩分鐘內在地圖上盡量圈出餐廳的標誌。當一分鐘時，我會叫你暫停並要求你換筆。明白嗎？

Subtest 2: Elevator Counting with distraction

在這個任務中，你同樣聽到電梯“嘟”聲，但這次會有兩種“嘟”聲，一種高，一種低。請不要理會高的“嘟”聲，只數低的“嘟”聲來數你去到了哪一層樓，就像上一個任務那樣。現在先試做兩個練習，讓你分清高和低“嘟”聲的區別。記住不要理會高的“嘟”聲，更不要數上高的“嘟”聲。每一串聲音都會先由低的“嘟”聲開始。現在先試做一次，準備好未？正確，你現在在第三層樓。現在再試做多一次，準備好未？現在，我想你聽另一串電梯“嘟”聲，並做相同的任務。

Subtest 3: Visual Elevator

請你想像你在一次旅行中，你決定住在一間多層樓高的大酒店。當你在酒店時，你發現電梯裏顯示你在哪層樓的顯示器壞了。請看這一系列圖片，每一張顯示了一個電梯。期

間會有一些大箭咀，就像這個。向下的箭咀表示電梯往下，此時你需要往下數。向上的箭咀表示電梯往上，你需要大聲數出電梯層。當你看到箭咀時，說“上”或“落”，避免你數上這些箭咀。當你講出數字時，我會依次指向每一幅圖片。請記著，箭咀不是樓層，它們只告訴你電梯的走向。所以，在第一個例子中，你會講“一-二-落-一-上-二”。現在你試做下。明白嗎？現在你再試下一個例子。現在請你開始看另一系列圖片做同樣的任務。請你盡快並準確地完成任務。請在數電梯時，大聲地數出來。

Subtest 4: Elevator Counting with Reversal

這個任務與上一個任務類似，但會比上一個任務複雜一點。請看看你剛剛所做的。還記得大箭咀告訴你電梯是上還是落嗎？現在，我們會做一個聲音版本的。這個任務裏，你可以通過聲音的高低嚟判斷電梯的走向。你會聽到三種聲音，一種是中音調，對應一層“樓”。第二種是高音調，對應上一個任務向上的箭咀。第三個是低音調，對應上一個任務向下的箭咀。請記住，中音表示你需要數的樓層，高音表示向上，低音表示向下。換句話講，中音調表示需要數的樓層，高音調表示電梯停止並向上走（所以你不數這個“嘟”聲）；低音調表示電梯停止並向下走（所以你同樣不數這個“嘟”聲）。明白嗎？現在，聽這個例子，我會示範，怎麼大聲數出來。‘一-二-上-三-四-落-三-二’所以答案是二。我只想你告訴我你最後到了哪一層樓。當你聽到高音調和低音調時，說‘上’和‘落’會幫你更好地完成任務。現在，試做下第二個例子。記住你並不一定要大聲數出來。我們想知道的是，當錄音裏問你‘你到了哪一層樓’時，你就回答到了哪一層樓。

Subtest 5: Telephone Search

想像你在度假，並且你住在你朋友的家。你會在他的家住幾個禮拜。你的朋友不在家，並且電話聯絡不到他。想像當你每次用廚房裏的洗碗盤時，都會發覺有嚴重的漏水。你需要找一個維修水喉的工人。有人告訴你，那些電話號碼前面帶有兩個相同符號的那些工人的技術是有保證的。你只要圈出兩個相同的符號。請你盡快並盡量準確地找出所有兩個相同的符號。當你完成時，請告訴我。當你做到最尾時，在右下角的方框內打叉，並放低筆。當你打上交叉後，你不能回看或者檢查之前做的。明白嗎？

Subtest 6: Telephone Search While Counting

這個任務,你同樣需要在電話黃頁中搜尋兩個相同的標誌,就好似在上一個任務中那樣。但這個任務中，我想你做另一個同樣重要的任務 – 數錄音所播放的一串聲音。當單獨做這個任務時，很容易可以數出有多少個聲音，但當你需要同時搜尋黃頁時，這個任務的難度會增加。在這個搜尋黃頁的任務中，想像你有興趣找出你所在地的餐廳。有人話比你知，帶有兩個相同標誌的餐廳是值得推薦的。現在，請你聽下你將會在錄音裏聽到的一個例子。請你盡快並準確地找出所有兩個相同的符號。當你完成時，在右下角的方框內打叉,就像你之前做的那樣。 你圈出兩個相同標誌的同時,你需要留心地聽聲音，而且當聲音停止時，你需要立刻告訴我你數了多少個聲音。記住，當你完成搜索時，在右下角的方框內打上勾，即使你仍在數聲音。記住，黃頁搜尋任務和數聲音任務是同樣重要的。請準備,當錄音裏說“準備”，請你開始這兩個任務。記住兩個任務同樣重要。而且不要忘記當錄音裏問‘幾多’的時候，你要立刻說出你數到了多少個聲音。

Instructions of the Attention Network Test (ANT)

你將會看到螢幕上出現一組組箭咀。你需要做的是留意中間箭咀的方向。當中間的箭咀指向左邊，請用左拇指按一下滑鼠的左鍵。當中間的箭咀指向右邊，請用右拇指按一下滑鼠右鍵。位於中間的箭咀會被另外四個箭咀包圍，你只需要留意中間箭咀的方向。在以上兩個情況按左鍵。在以上兩個情況按右鍵。在螢幕最中間會有一個十字符號，箭咀會出現在十字符號的上方或下方。在箭咀即將出現前，你可能會看到一個閃動的星形符號。星形符號可能會與中間的十字符號出現在同一位置、或十字符號的上方、或十字符號的下方。現在有一些示範。這實驗會量度你的反應時間和準確度，請你盡量快速而準確地回應。現在會有一個簡短的練習。實驗會有三個部分，實驗即將開始，你準備好未？

Instructions of the test of attentional shifting

每次你會聽到一串聲音。 當你聽到這一串聲音裏面，高低音交替地出現時，按 1，再按 Enter。當你聽到這一串聲音裏面，高低音同時地播放時，按 2，再按 enter。明白嗎？

Instructions of the backward digit span test

你將會聽到一些數字序列，請你反方向地重複這些數字，例如我講一-二-三，你要講三-二-一。第一條題目會由兩個數目字組成，每兩條遞增一個數目字，最長會有九個數目。

Instructions of WAIS-IV visual working memory subtests

Subtest 1: Symbol Search

看一下這些圖形。其中一個圖形與這裡其中一個圖形是一樣的，所以我在這個圖形上劃一條斜線，就像這樣。看一下這些圖形。這個圖形與這個圖形是一樣的，所以我在這個圖形上劃一條斜線，就像這樣。現在看這些圖形。在這裡，沒有圖形與這裡的圖形是一樣的，所以我在 NO 這裡劃一條斜線，就像這樣。如果你看到一個圖形與這裡其中的一個圖形一樣的話，在這個圖形上劃一條斜線。如果你沒有看到任何圖形與與這裡其中一個圖形一樣的話，在 NO 方格上劃一條斜線。 當我說開始時，用同樣的方法完成任務。從這裡開始，按順序做，請不要跳過任何題目。請你盡量快速而準確地作答直到我叫你停止為止。當你完成了第一頁，就去做下一頁。你準備好了嗎？

Subtest 2: Coding

看這些方格。每個方格的上半部份有一個數字，下半部份有一個特殊的符號。每個數字都有它自己對應的符號。在這裡，方格的上半部份有數字，但是下半部份是空的。你需要將對應的符號填在這些空的方格內，就像這樣。這個是 6，6 對應的是這個符號，所以我將這個符號填在這個方格內，就像這樣。這個是 8，8 對應的是這個符號，所以我將這個符號填在這個方格內，就像這樣。這個是 3，3 對應的是這個符號，所以我將這個符號填在這個方格內，就像這樣。現在，你試做這些，當你做到這條線的時候，停止。當我說開始時，用同樣的方法完成任務。從這裡開始，按順序做，請不要跳過任何題目。請你盡量快速而準確地作答直到我叫你停止為止。你準備好未？

Subtest 3: Cancellation

Item A: 看一下這些圖形。這是個紅色的正方形，這是個黃色的三角形。 現在看一行。這裡有正方形和三角形，但有些圖形的顏色是不一樣的。我會看這一行的圖形，在每一個紅色的正方形或黃色的三角形上劃一條斜線。我不會在其他圖形上劃斜線。現在你做這些。在每一個紅色的正方形或黃色的三角形上劃一條斜線。不要在其他圖形上劃斜線。當你完成了第一行的時候，接著做第二行。請你盡量快速而準確地作答。你不可以回看之前的圖形。你準備好了嗎？當我說開始時，在每一個紅色的正方形或黃色的三角形上劃一條斜線。從這裡開始，並按順序做。當你完成了第一行的時候，接著做第二行。請你儘量快速而準確地作答。你不可以回看之前的圖形。如當我叫停時，你要立刻停止，并請出你最後在看的圖形。你準備好未？

Item B: 看一下這些圖形。這是個橙色的星星，這是個藍色的圓圈。現在看這一行。這裡有星星和圓圈，但有些圖形的顏色是不一樣的。我會看這一行的圖形，在每一個橙色的星星或藍色的圓圈上劃一條斜線。我不會在其他圖形上劃斜線。現在你做這些。在每一個橙色的星星或藍色的圓圈上劃一條斜線。不要在其他圖形上劃斜線。當你完成了第一行的時候，接著做第二行。請你儘量快速而準確地作答。你不可以回看之前的圖形。你準備好了嗎？當我說開始時，在每一個橙色的星星或藍色的圓圈上劃一條斜線。從這裡開始，並按順序做。當你完成了第一行的時候，接著做第二行。請你儘量快速而準確地作答。你不可以回看之前的圖形。如當我叫停時，你要立刻停止，并請出你最後在看的圖形。你準備好未？

Appendix B.

Descriptions of the Test of Everyday Attention (TEA)

The six subtests were as follows:

1) *Map search*. Participants searched for symbols, e.g. a knife-and-fork sign representing eating facilities, on a colored map. The raw scores were the total number of symbols (out of eighty) found in the first minute and in two minutes. This task assessed selective attention in the visual modality.

2) *Elevator counting with distraction.* Participants were asked to count the low tones in the imaginary elevator while ignoring the high tones. The raw score was indicated by the number of strings correctly counted. This task assessed sustained attention in auditory modality.

3) *Visual elevator.* Participants were asked to count up and down as they followed a series of visually presented "floors" in the elevator. It was a self-paced task. The raw scores were the number of correct responses and the time-per-switch measure. Switch was the number of times the elevator switched from going up to going down and vice versa. This task assessed attentional switching in the visual modality.

4) *Elevator counting with reversal.* This test was similar to the Visual Elevator subtest except that the instruction was presented at a fixed speed on audio tape. Participants were asked to count strings of "medium" pitched tones. Interspersed with these "medium" pitched tones were both high (indicating that the participants must switch to count up) and low tones (indicating that participants must switch to count down). The raw score was the number of strings of tones correctly counted. This task assessed attentional switching in the auditory modality.

5) *Telephone search.* Participants looked for key symbols while searching for plumbers in a simulated telephone directory. The raw score was calculated by dividing the total time

taken by the number of symbols detected. This task assessed visual selective attention.

6) *Telephone search dual task.* Participants looked for key symbols while searching for plumbers in a simulated telephone directory. The raw score was calculated by dividing the total time taken by the number of symbols detected. This task assessed divided attention in the auditory and visual domains.

Scoring system of the Attention Network Test (ANT)

There are three raw scores. Firstly, the alerting effect was calculated by subtracting the mean reaction time of the alerting-cue conditions from that of the no-cue conditions. Secondly, the orienting effect was calculated by subtracting the mean reaction time of the spatial-cue conditions from that of the alerting-cue conditions. Thirdly, the executive control was calculated by subtracting the mean reaction time of all congruent flanking conditions, summed across cue types, from the mean RT of incongruent flanking conditions.

Description of the WAIS-IV visual working memory subtests

The three subtests were as follows:

1) *Symbol search*. Participants were asked to scan a search group and indicate whether one of the symbols in the target group matched with one in the search group within two minutes. The raw score was the number of incorrect responses subtracted from correct responses.
2) *Coding*. Participants copied symbols which were paired with numbers using a key within two minutes. The raw score was the number of symbols correctly copied.
3) *Cancellation*. Participants marked target shapes while scanning through rows of shapes with different colors. The time limit of each item was 45 seconds and there were two items. The raw score was the number of correct responses minus incorrect responses.